Multiple Heavy Quarks production: experiment

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XIIth Meeting on B Physics.Tensions in Flavour measurements: a path toward Physics beyond the Standard Model

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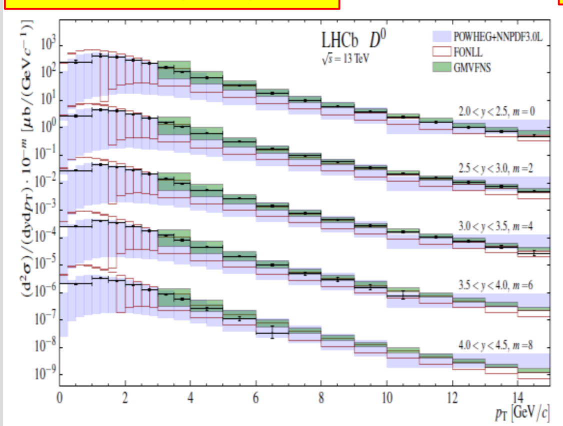
Europe/Rome timezone

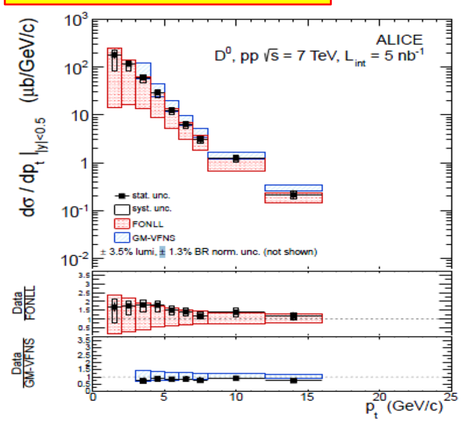
High energy ~~hadron~~ gluon collision

- Heavy flavour production at LHC is dominated by gg-fusion process
- Quarkonia: reasonably (rapidly improving) agreement with NR QCD
  - J/ψ, ψ', η_c, $\chi_{c1,2}$, $\chi_{b1,2}(nP)$, ….
- Open flavour, charm and beauty:
  - CDF, ATLAS, ALICE, LHCb,… vs FONLL, POWHEG, GMVFNS,…

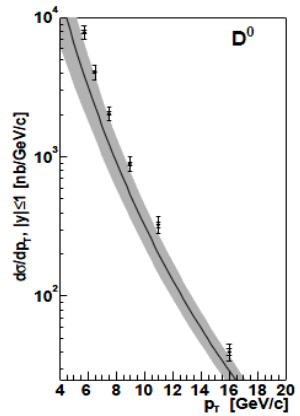
JHEP 1603(2016) 159



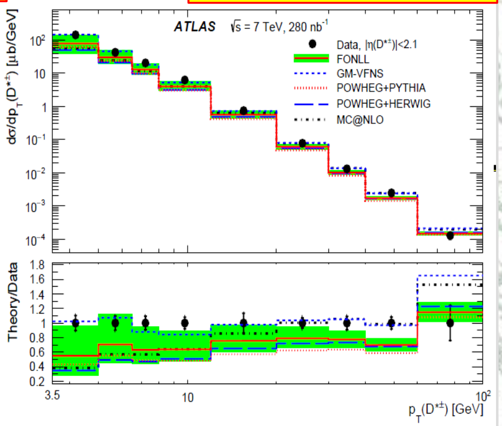
JHEP 1201(2012) 128



JHEP 1207(1012) 191



NPB 907 (2016) 717

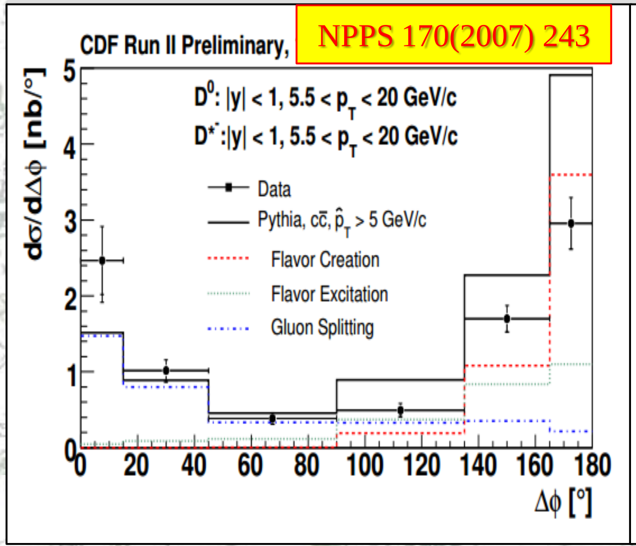


- Good job: both experimental and the theory!

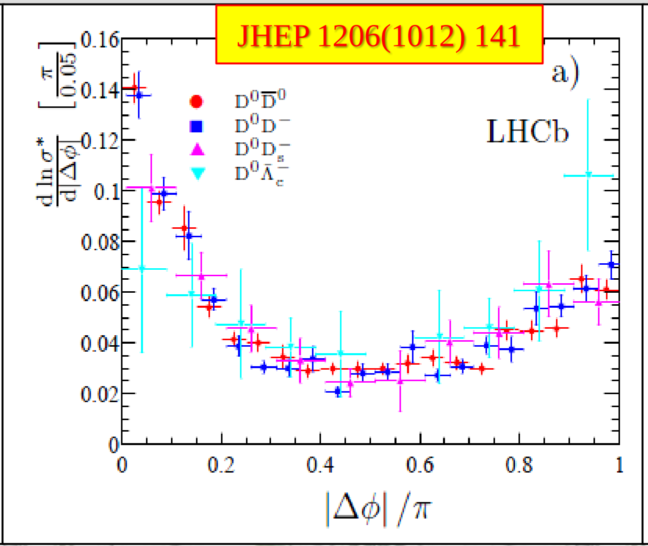
Single particle spectra

- ☹ Not so many observables …
- ☹ Relatively low sensitivity to high-order effects for open-flavour hadrons
- ☺ Correlations of two hadrons: much more variables!
  - Direct probe for various subprocesses

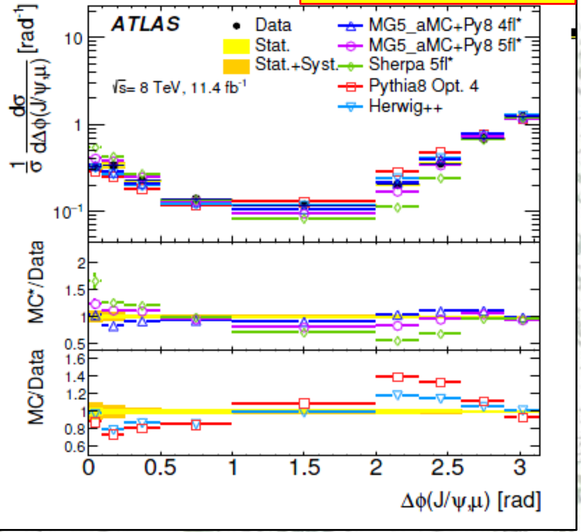
NPPS 170(2007) 243



JHEP 1206(1012) 141



arXiv:1705.03374



Multiple HQ?

PLB 114 (1982) 457

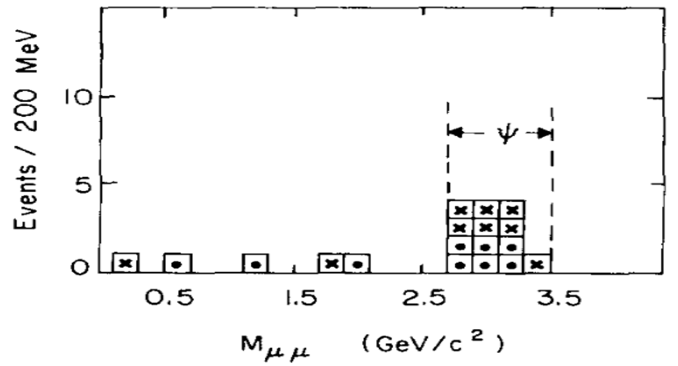
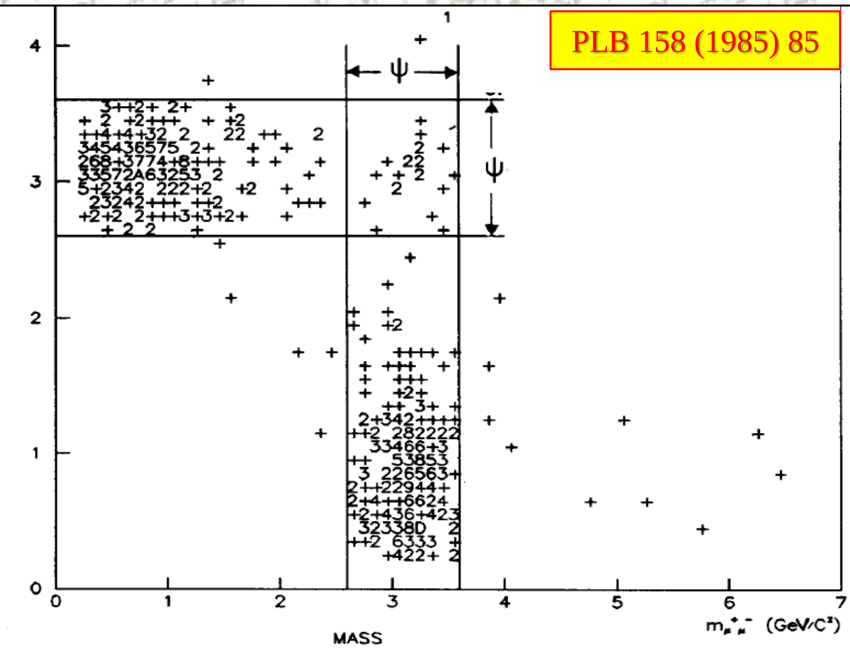


Fig. 2. Quadrimuon events produced in the platinum target: mass spectrum of $\mu\mu$ pairs produced together with a J/ψ. 150 GeV/c data: squares with a dot. 280 GeV/c data: squares with a cross.

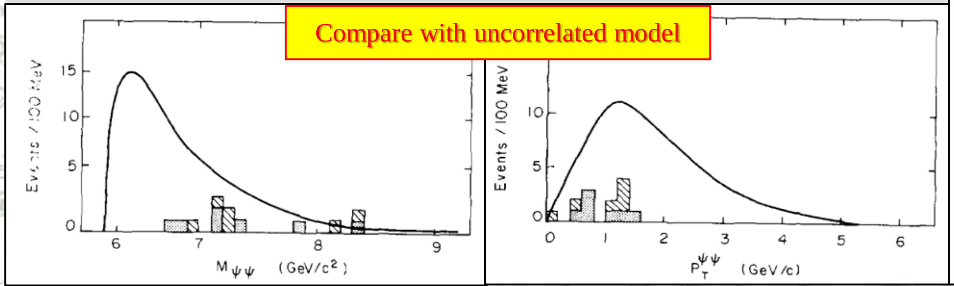
PLB 158 (1985) 85



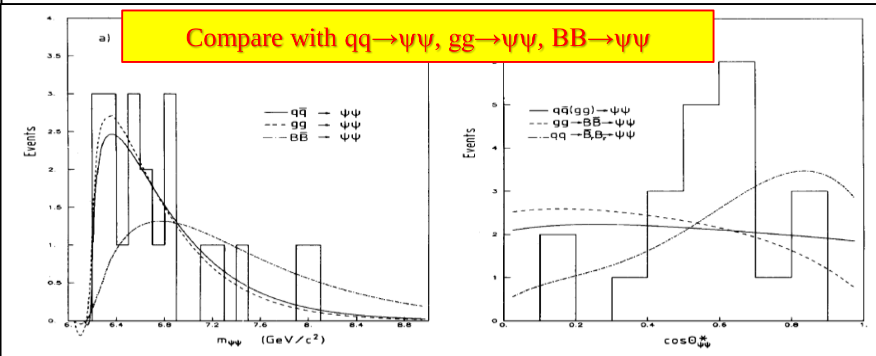
NA3 : $\sigma(J/\psi J/\psi)/\sigma(J/\psi) = (3.0\pm1.0)\times10^{-4}$

- πPt: 13 $J/\psi J/\psi$
- pPt: 15±4 $J/\psi J/\psi$

Compare with uncorrelated model



Compare with qq→ψψ, gg→ψψ, BB→ψψ



Multiple HQ? Open flavour

PLB 187 (1987) 185

WA75

- 350 GeV/c π^-
- emulsion
- 2 events
- 200 D candidates

…not so rare

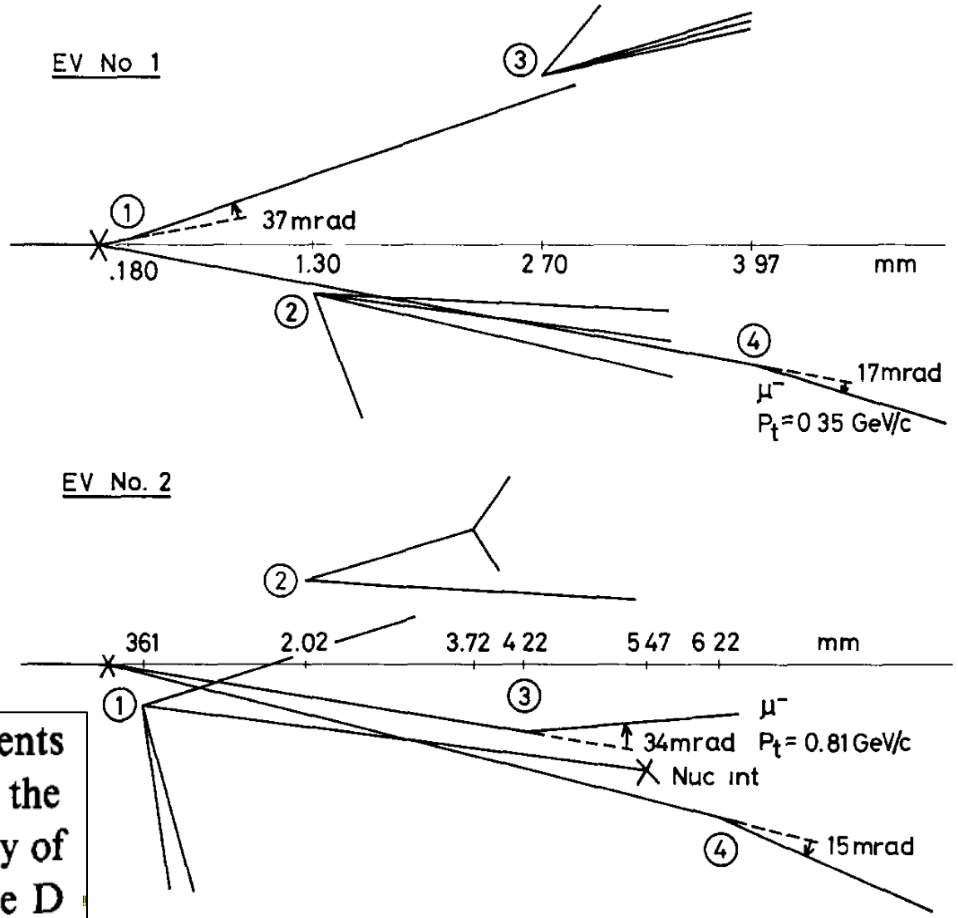


Fig. 1. Sketches of the events

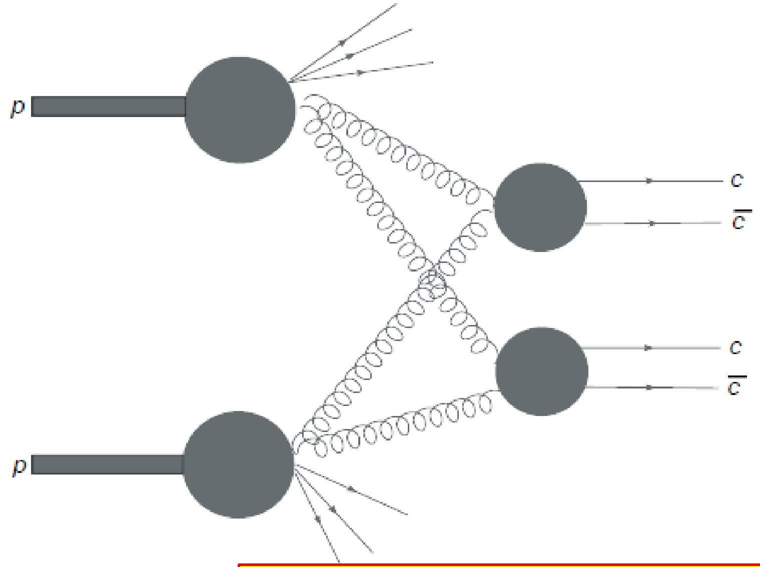
Discussion and conclusions. For both the events reported above, the most natural interpretation is the simultaneous emission and the subsequent decay of four charmed particles, assumed hereafter to be D mesons. In both cases a rather energetic D^- is seen

Why multiple HQ?

- More observables, large sensitivity to QCD corrections
- $2\times J/\psi$, $J/\psi+\Upsilon$: good way to probe the role of *Colour Octet*
- $2\times J/\psi$: palette of theory calculations
  - incomplete NLO* *Colour Singlet*
  - LO + k_T
  - LO CO
  - full NLO
- $J/\psi, \Upsilon + (c\bar{c})$
  - NRQCD, k_T, CO, …
- $2\times(c\bar{c})$: k_T

+ Double Parton Scattering

DPS: simple paradigm



Two independent hard scattering processes
Relations through (unknown) *double* PDF

$$\Gamma_{ij}(x_1, x_2; \mathrm{b}_1, \mathrm{b}_2; Q_1^2, Q_2^2) = D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) f(\mathrm{b}_1) f(\mathrm{b}_2),$$

Assume factorization of *double* PDFs

$$D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) = D_h^i(x_1; Q_1^2) D_h^j(x_2; Q_2^2).$$

(Can't be true for all x, Q^2)

Easy to make predictions!
And the predictions are easy to test

Pocket formula

$$\sigma_{\mathrm{DPS}}^{AB} = \frac{m}{2} \frac{\sigma_{\mathrm{SPS}}^{A} \sigma_{\mathrm{SPS}}^{B}}{\sigma_{\mathrm{eff}}}.$$

m=1,2

Universal (energy and process independent) factor)

$$1/\sigma_{eff} = \int d^2b F^2(b)$$

$$\sigma_{\mathrm{eff}}^{\mathrm{DPS}} = 14.5 \pm 1.7^{+1.7}_{-2.3}\ \mathrm{mb}$$

CDF, F.Abe *et al*., PDR 56 3811 (1997)

DPS

- Simple pattern, a lot of powerful consequences and interesting predictions
- *Pocket formula* is also ***valid for differential cross-sections***

$$\sigma^{\mathrm{DPS}}(pp \to c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{\mathrm{eff}}}\sigma^{\mathrm{SPS}}(pp \to c\bar{c}X_1)\cdot\sigma^{\mathrm{SPS}}(pp \to c\bar{c}X_2).$$

$$\frac{d\sigma^{\mathrm{DPS}}(pp \to c\bar{c}c\bar{c}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t} dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{1}{2\sigma_{\mathrm{eff}}}\cdot\frac{d\sigma^{\mathrm{SPS}}(pp \to c\bar{c}X_1)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}}\cdot\frac{d\sigma^{\mathrm{SPS}}(pp \to c\bar{c}X_2)}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}}.$$

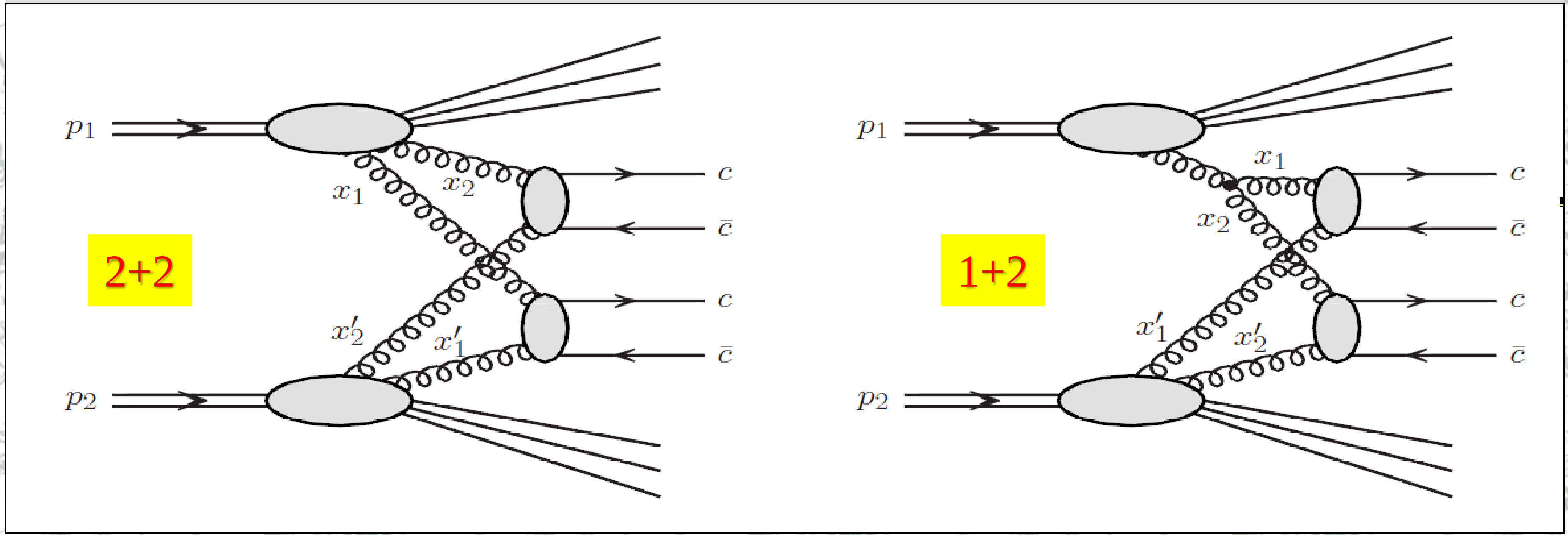
- The effective cross-section is a property of proton (integral over transverse degrees of freedom)
  - Smaller than "*proton size*": $\pi R^2 \approx 50\mathrm{mb}$
  - It is universal: ***energy and process independent***
    - easy to compare Tevatron, GPD and LHCb

$\sigma_{\mathrm{eff}} \sim \frac{1}{4}\,\sigma_{\mathrm{in}}$ production of cross-section for A+B is enhanced with ***factor of four*** with respect to naïve model

- Large role at "low" p_T, decreases with p_T
  - with HQ, the measurements can be performed at low p_T, up to 0

Is σ_{eff} really a constant?

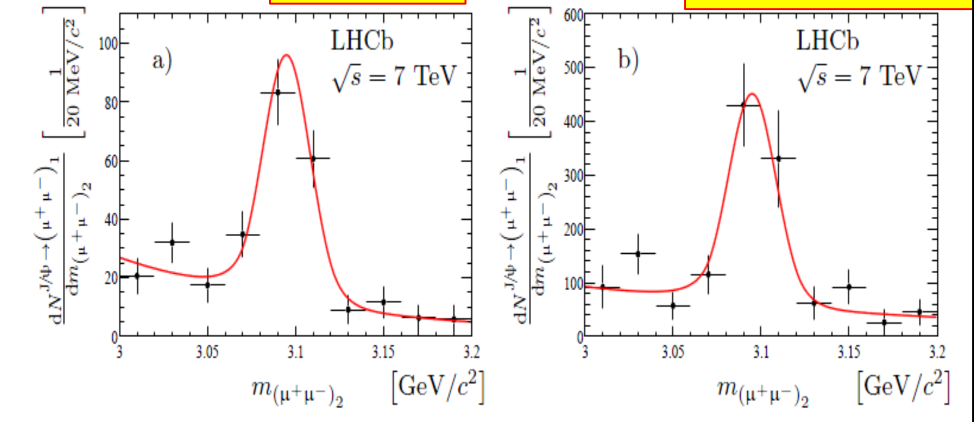
- There is calculable contribution from 1+2
- Correlations, large dependency on scale
  - Stabilization for low x-processes Blok, Strikman, arXiv:1611.03649
  - *Probing of universality of* σ_{eff} is important for understanding of proton structure and QCD at high parton densities



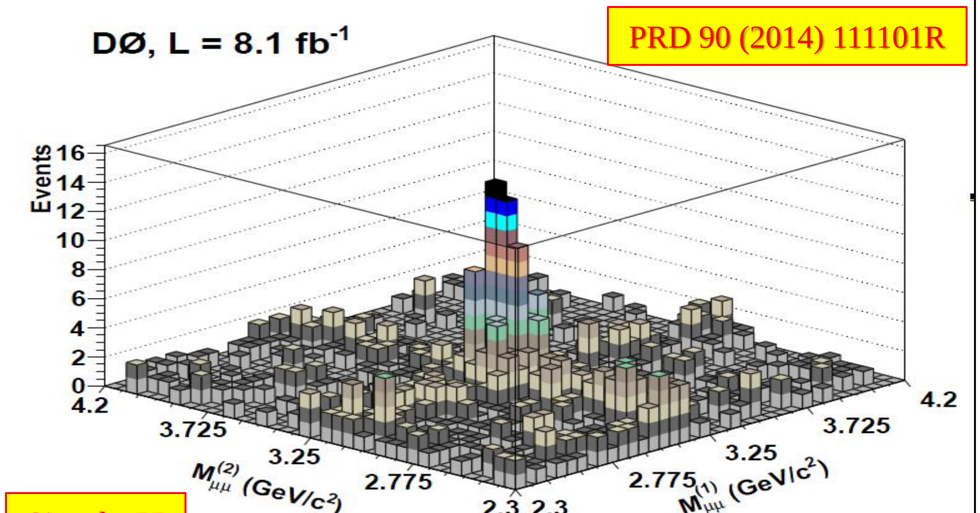
2×J/ψ signals after >30 years of silence

Signal ~100

PLB 707 (2012) 52



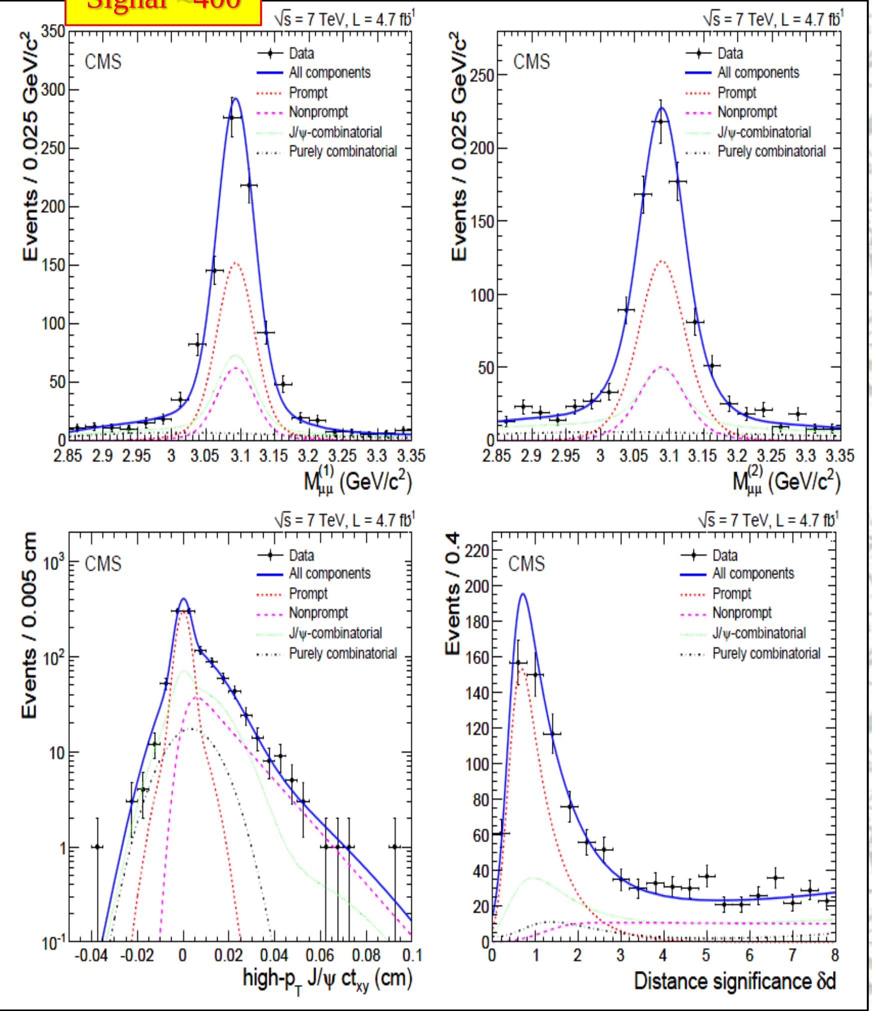
PRD 90 (2014) 111101R



Signal ~55

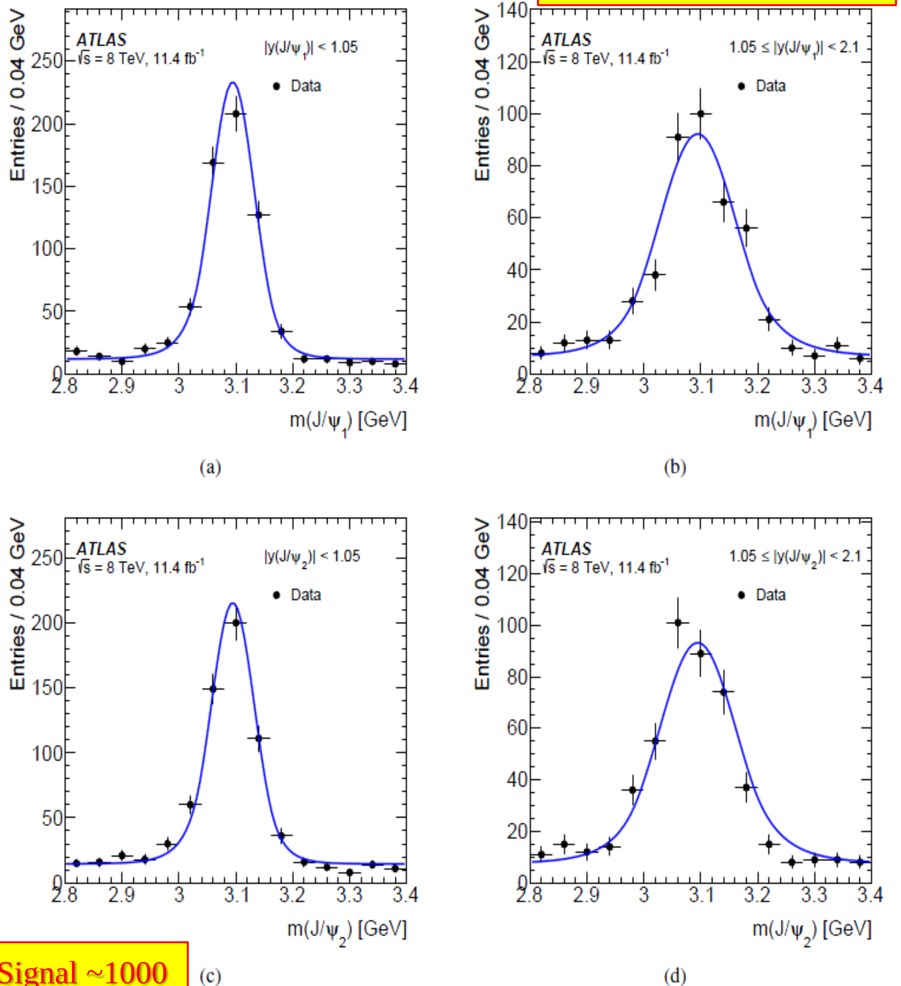
Signal ~400

JHEP 1409 (2014) 094



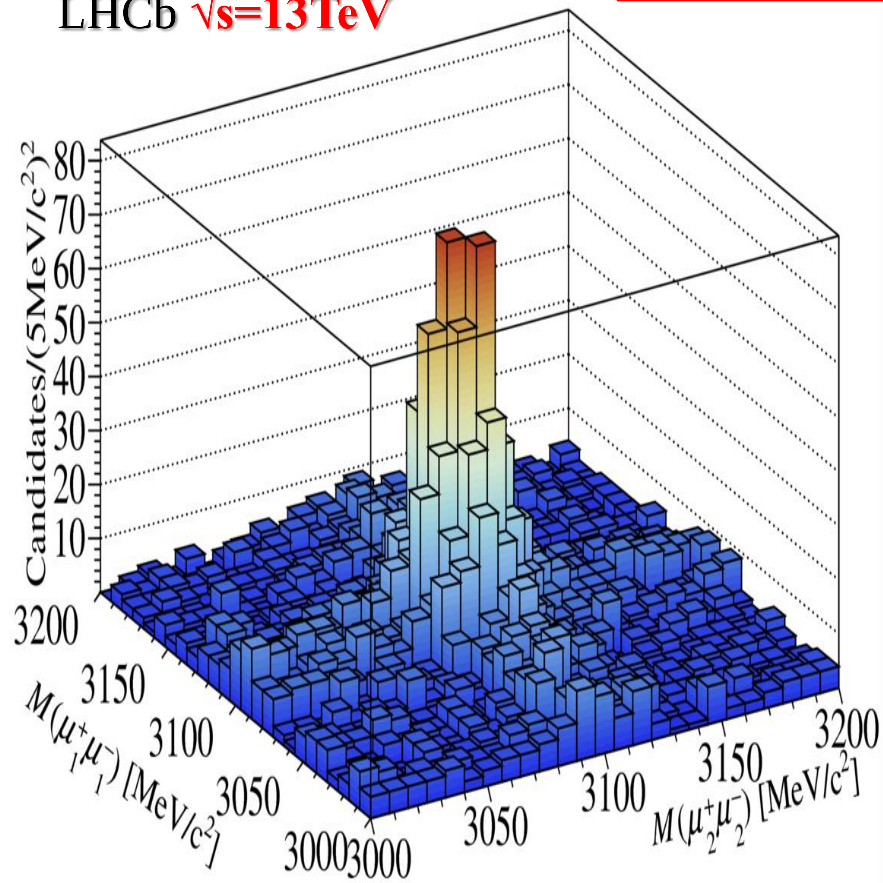
2×J/ψ signals after >30 years of silence

EPJC 77 (2017) no.2, 76



Signal ~1000

arXiv:1612.07451



Signal ~1000

2×J/ψ in numbers

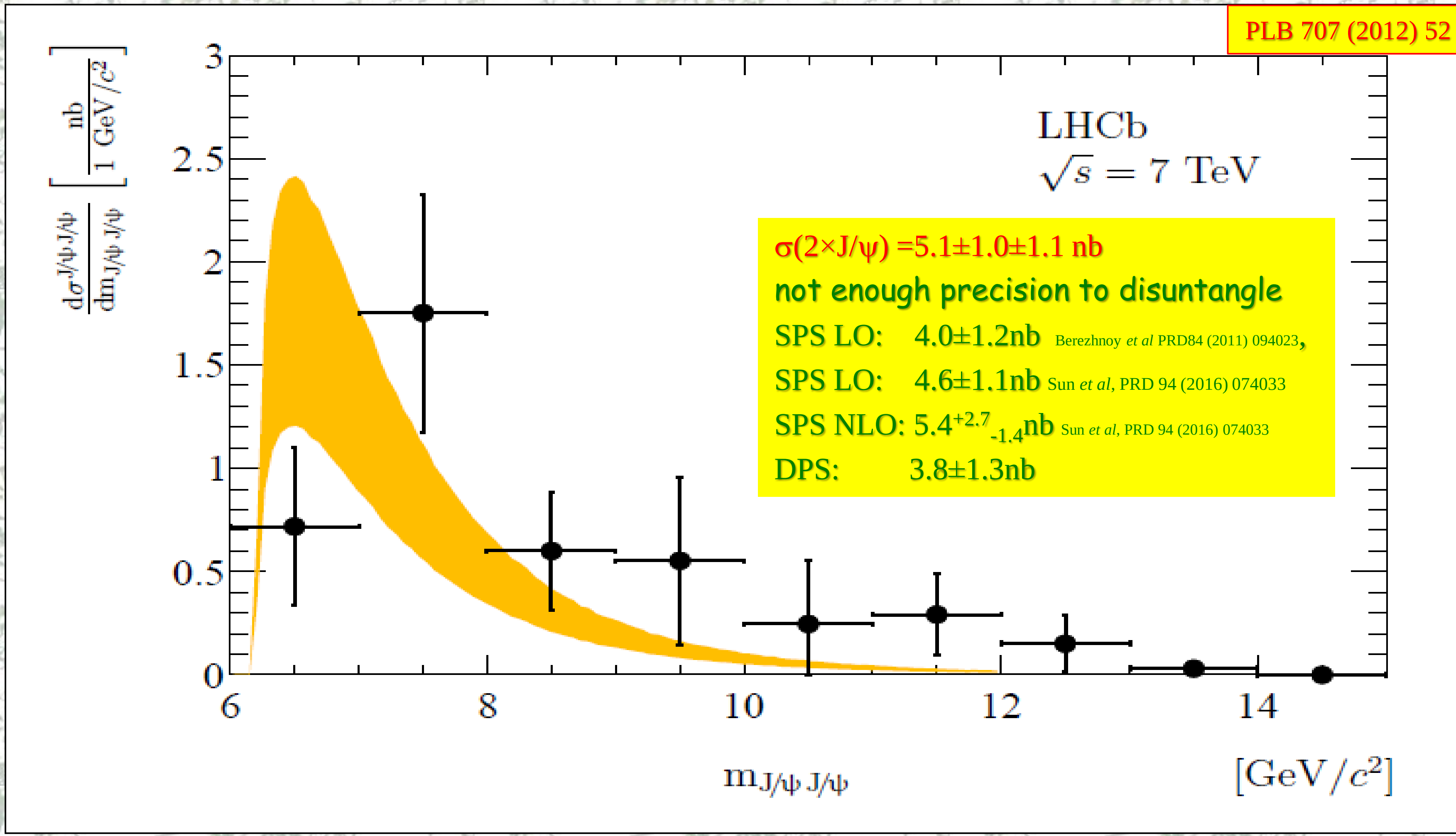
	LHCb	CMS	D0	ATLAS	LHCb
√s	7TeV	7TeV	1.96TeV	8TeV	13TeV
Lumi	$38pb^{-1}$	$4.73fb^{-1}$	$8.10fb^{-1}$	$1.41fb^{-1}$	$279pb^{-1}$
y(J/ψ)	2<y<4.5	|y|<2.2	|y|<2.0	|y|<2.1	2<y<4.5
p_T(J/ψ)	<10 GeV/*c*	>4.5 GeV/*c*	>4.0 GeV/*c*	>8.5 GeV/*c*	<10 GeV/*c*
Signal	141±19	446±23	*O*(55)	1160±70	$(1.05\pm 0.05)\times 10^3$
f_{DPS}		*O*(10%)	(42±12) %	(9.2±2.1±0.5)%	(50–100)%

- 4 muon final state:
  - easy to trigger, low background, high efficiency
- Complementary acceptances: (very) different *x*-regions
- *No* vs *high*-p_T cut: different DPS contamination

None of LHC experiments used full Run-I/Run-II dataset

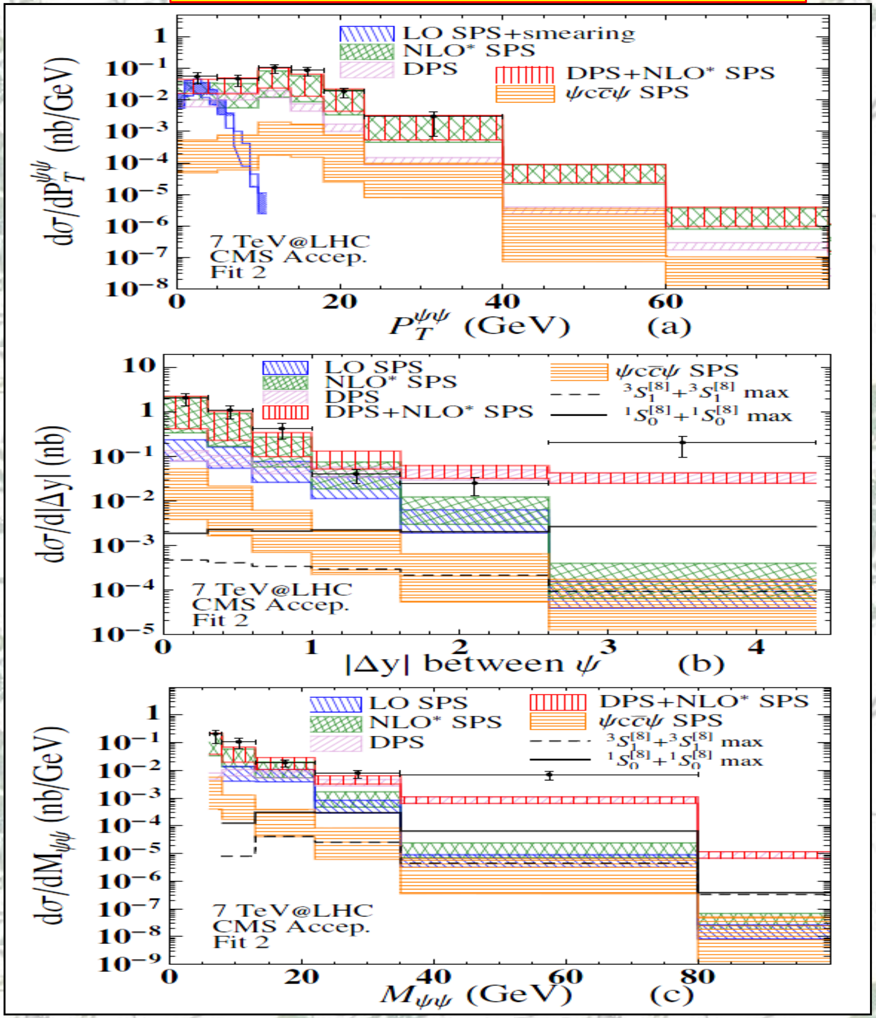
Significant increase in statistic could be expected

$2\times J/\psi$ LHCb @ 7TeV



2×J/ψ CMS @ 7TeV

JHEP 1409 (2014) 094 + PLB 751 (2015) 479



$\sigma(2\times J/\psi) = 1.49\pm0.07\pm0.13$ nb

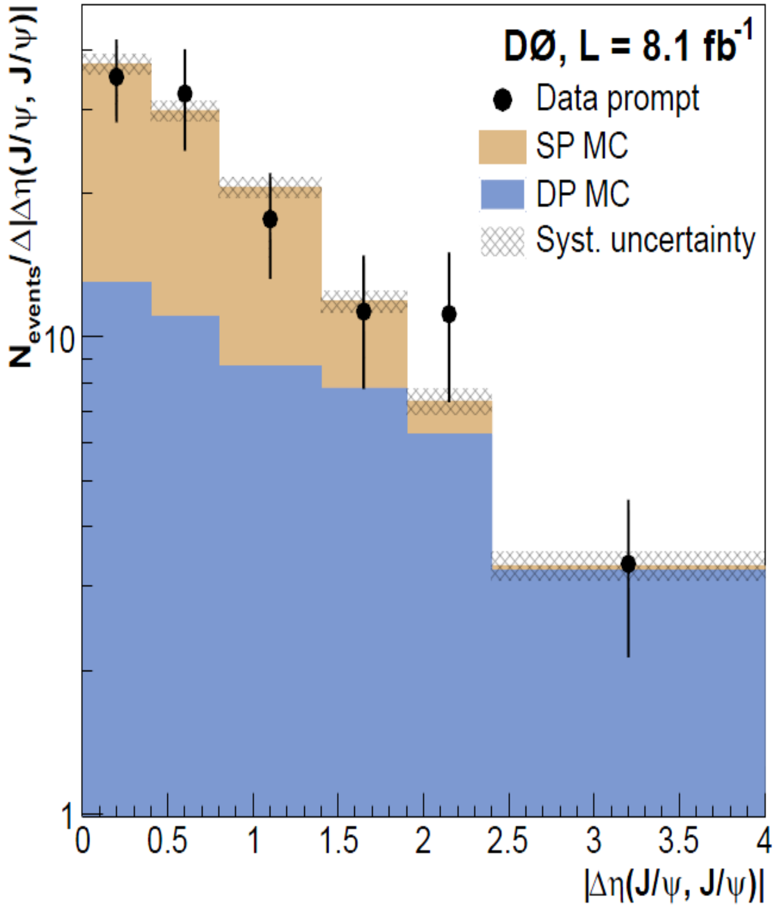
$p_T(2\times J/\psi)$, $\Delta y(2\times J/\psi)$, $m(2\times J/\psi)$ distributions are analysed by *Lansberg&Shao* NLO* CS

- Importance of α_s^5
- No large CO contribution
- To accommodate large Δy DPS is needed

$\sigma_{eff} = 11\pm2.9$mb

$2\times J/\psi$ D0 @ 1.96TeV

PRD 90 (2014) 111101R



$\sigma(2\times J/\psi) = 129\pm11\pm37$ fb

- SPS: $59\pm6\pm22$ fb
- DPS: $70\pm6\pm22$ fb

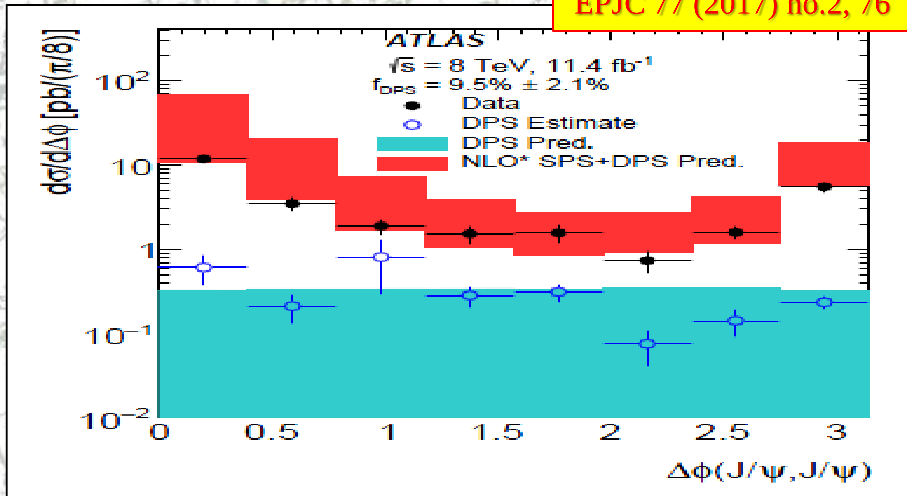
Prediction:

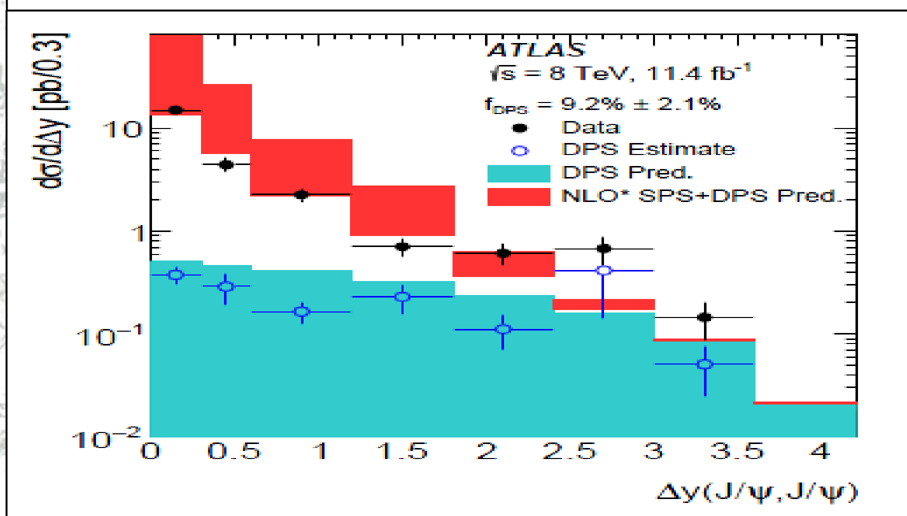
- SPS LO 51.9 fb Qiao, Sun, CPC37 (2013) 033105
- SPS kT 55.1 fb Baranov, PRD87 (2013) 034035
- SPS NLO* 90^{+180}_{-50} fb Lansberg,Shao, PRL 111(2013) 122001
- DPS 17.6 ±13fb

$\sigma_{eff} = 4.8\pm0.5\pm2.5$mb

2×J/ψ ATLAS @ 8TeV

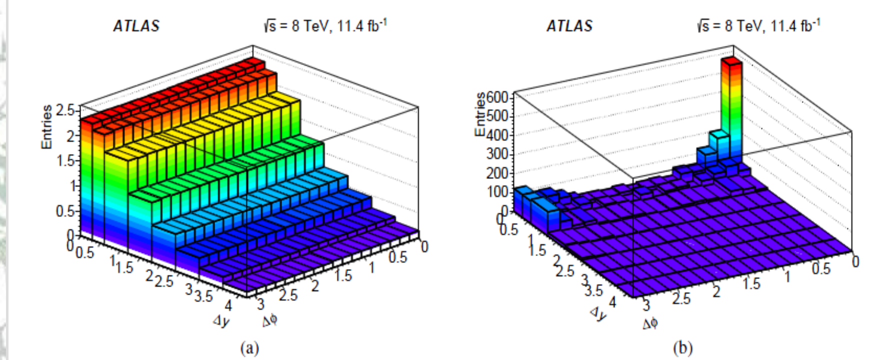
EPJC 77 (2017) no.2, 76





$\sigma(2\times J/\psi) = 160\pm12\pm14$ pb

- ***Model-independent*** **SPS vs DPS separation**

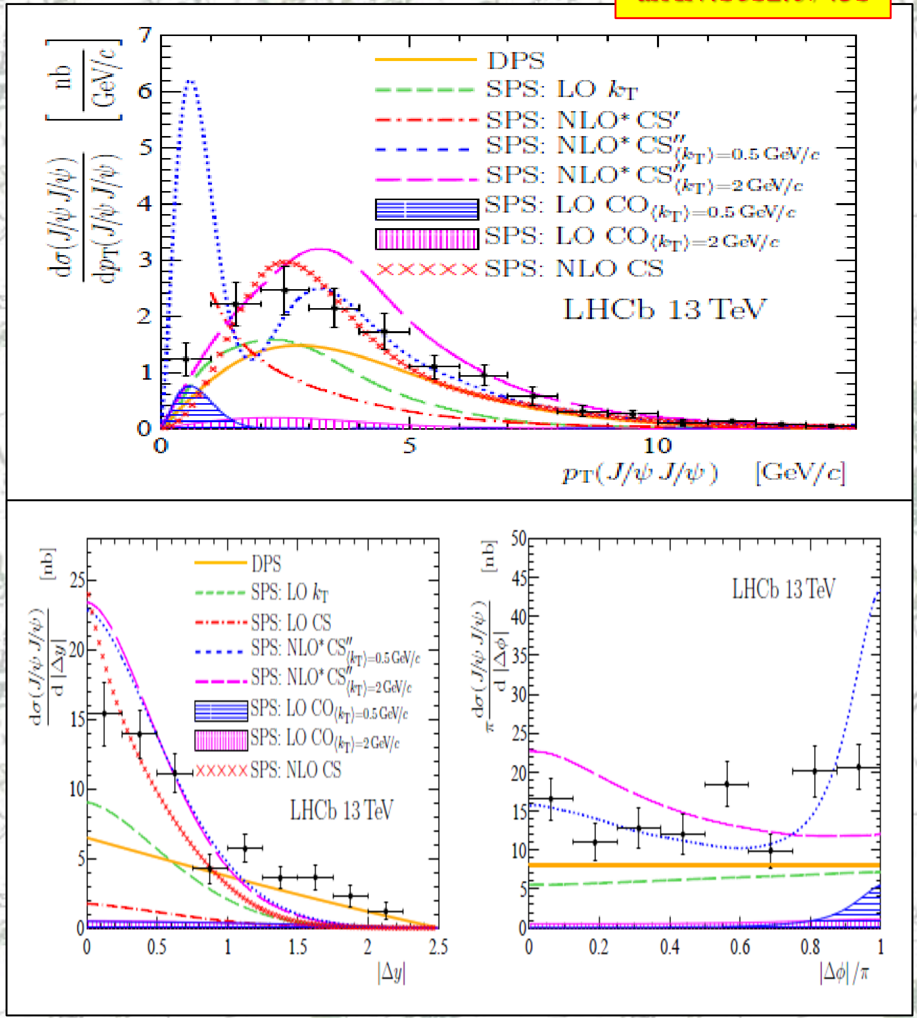


- DPS: 14.8 ±3.5 ±1.5pb

  $\sigma_{eff} = 6.3\pm1.6\pm1.0$mb

2×J/ψ LHCb @ 13TeV

arXiv:1612.07451



$\sigma(2\times J/\psi) = 15.2 \pm 1.0 \pm 0.9$ nb

SPS predictions:

- LO CS 1.3nb Likhoded *et al*, PRD94 (2016) 054017
- LO CO 0.45nb Shao, PC 184 (2013) 2562
- NLO* CS 15nb Lansberg,Shao, PLB751(2015) 479
- NLO CS 12nb Sun, Han, Chao, PRD94 (2016) 074033
- DPS: 8.1nb

2×J/ψ LHCb @ 13TeV

arXiv:1612.07451

f_{DPS}[%]

Variable	LO CS	LO k_T	NLO* CS′	NLO* CS″ $\langle k_T \rangle = 2\,\text{GeV}/c$	NLO* CS″ $\langle k_T \rangle = 0.5\,\text{GeV}/c$	NLO CS
no $p_T(J/\psi\, J/\psi)$ cut						
$p_T(J/\psi\, J/\psi)$	—	78 ± 3	—	88 ± 56	81 ± 7	—
$y(J/\psi\, J/\psi)$	83 ± 39	—	—	75 ± 37	68 ± 34	—
$m(J/\psi\, J/\psi)$	76 ± 7	74 ± 7	—	78 ± 7		77 ± 7
$\lvert\Delta y\rvert$	59 ± 21	61 ± 18	—	63 ± 18	61 ± 18	69 ± 16
$p_T(J/\psi\, J/\psi) > 1\,\text{GeV}/c$						
$y(J/\psi\, J/\psi)$	—	—	75 ± 24	71 ± 38	68 ± 34	—
$m(J/\psi\, J/\psi)$	—	73 ± 8	76 ± 7	88 ± 1		—
$\lvert\Delta y\rvert$	—	57 ± 20	59 ± 19	60 ± 18	60 ± 19	—
$p_T(J/\psi\, J/\psi) > 3\,\text{GeV}/c$						
$y(J/\psi\, J/\psi)$	—	—	77 ± 18	64 ± 38	64 ± 35	—
$m(J/\psi\, J/\psi)$	—	76 ± 10	84 ± 7	87 ± 2		—
$\lvert\Delta y\rvert$	—	42 ± 25	53 ± 21	53 ± 21	53 ± 21	—

σ_{eff}[mb]

Variable	LO k_T	NLO* CS″ $\langle k_T \rangle = 2\,\text{GeV}/c$	NLO* CS″ $\langle k_T \rangle = 0.5\,\text{GeV}/c$	NLO CS
$p_T(J/\psi\, J/\psi)$	11.3 ± 0.6	10.1 ± 6.5	10.9 ± 1.2	—
$y(J/\psi\, J/\psi)$	—	11.9 ± 7.5	10.0 ± 5.0	—
$m(J/\psi\, J/\psi)$	10.6 ± 1.1	10.2 ± 1.0		10.4 ± 1.0
$\lvert\Delta y\rvert$	12.5 ± 4.1	12.2 ± 3.7	12.4 ± 3.9	11.2 ± 2.9

f_{DPS} is large >50%

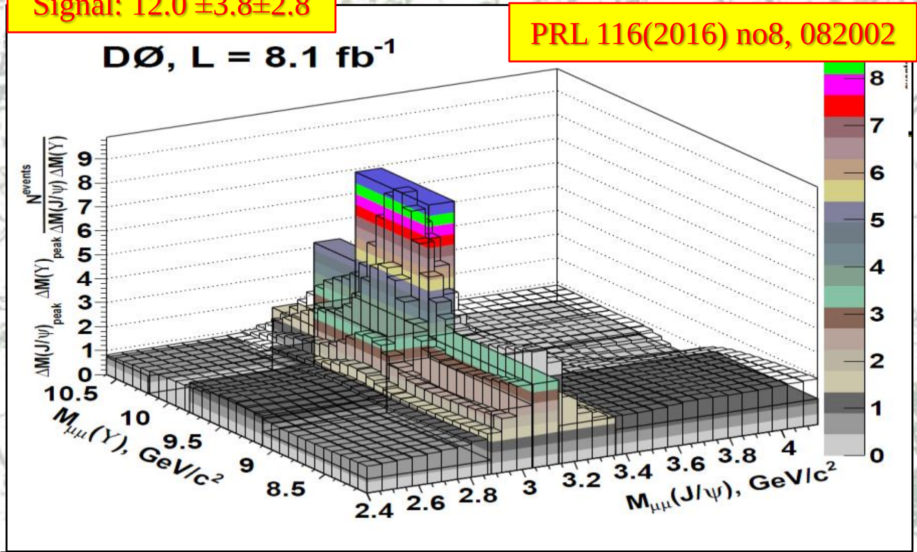
σ_{eff} is *almost* model independent ±1mb

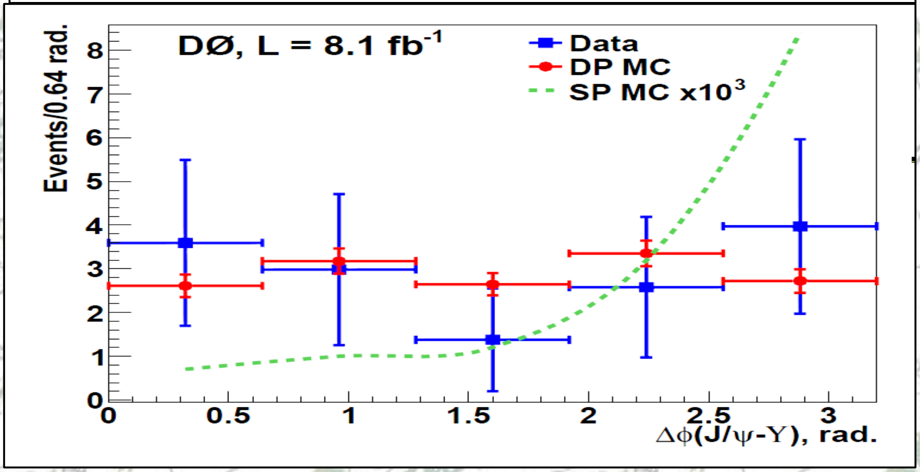
CO is small (if any)

$J/\psi+\Upsilon$ D0 @ 1.96TeV

Signal: 12.0 ±3.8±2.8

PRL 116(2016) no8, 082002





- Very interesting final state: no SPS LO CS diagrams!

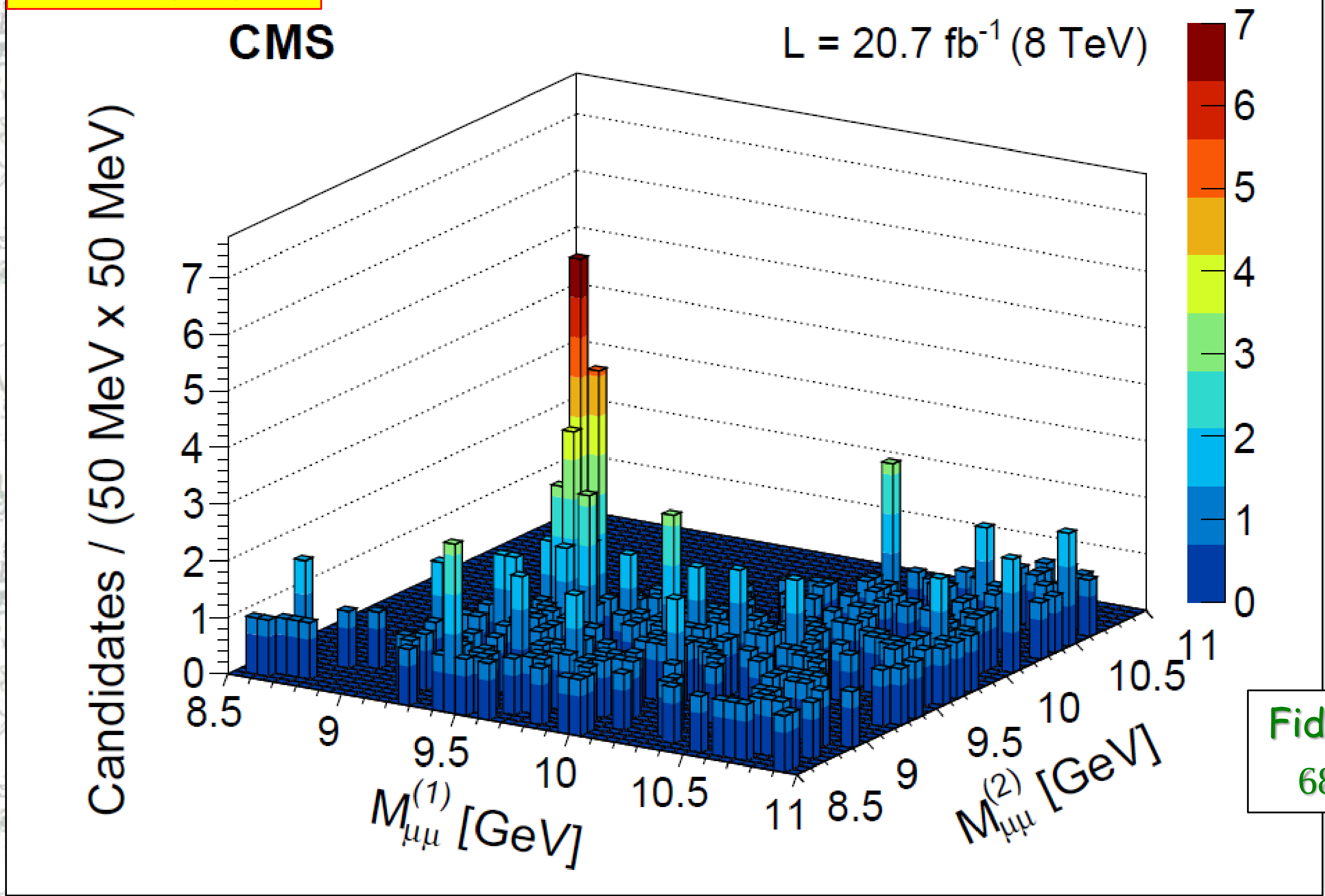
$$\sigma(J/\psi+\Upsilon) = 27\pm9\pm7\ \text{nb}$$

- Uniform $\Delta\phi$ suggest DPS dominance

$$\sigma_{eff} = 2.2\pm0.7\pm0.9\text{mb}$$

$2\times\Upsilon$ CMS @ 8TeV

JHEP 1705 (2017) 013



Fiducial cross-section:

68.8±12.7±7.4±2.8 pb

σ_{eff} = 2.2–6.6mb

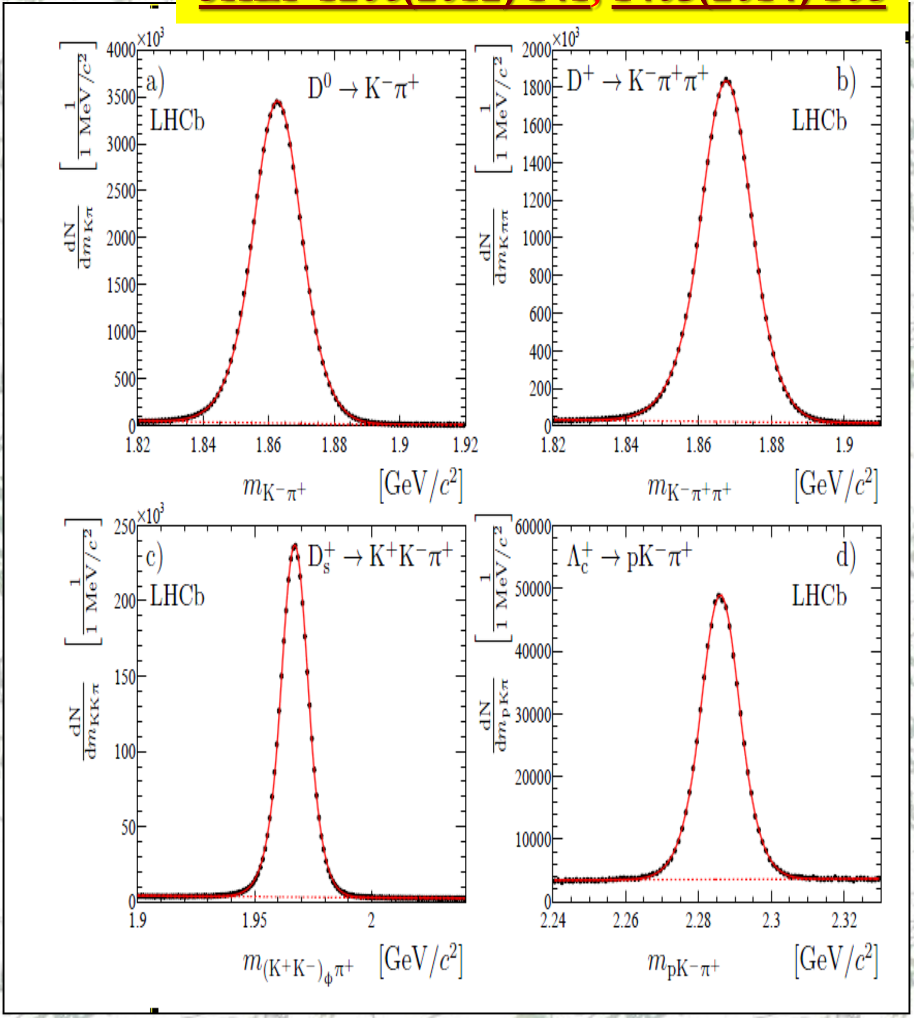
$J/\psi + c\bar{c}$ and $2\times c\bar{c}$

JHEP 1206(2012) 141, 1403(2014) 108

Measurements with open charm hadrons

- Unique feature of LHCb experiment:
- Infinite statistics of charm mesons
- low background
- hadron identification
- efficient trigger

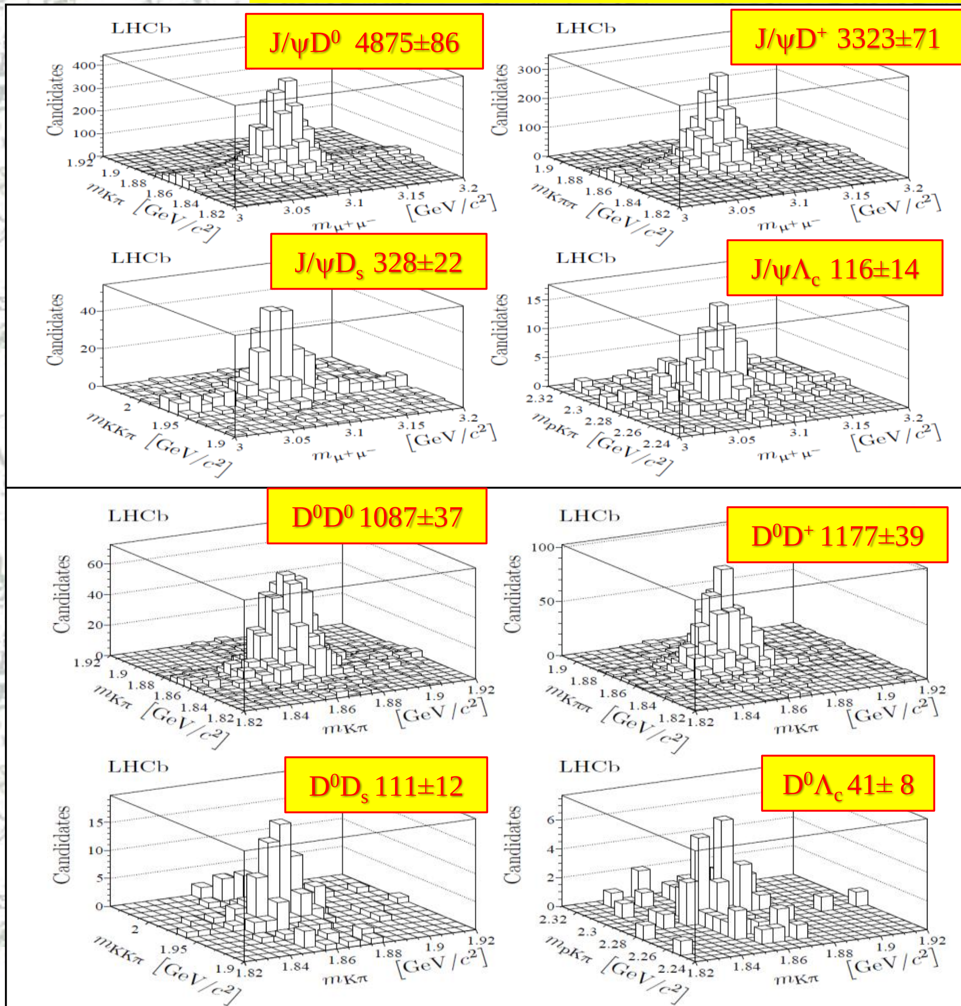
… and even better for Run-II

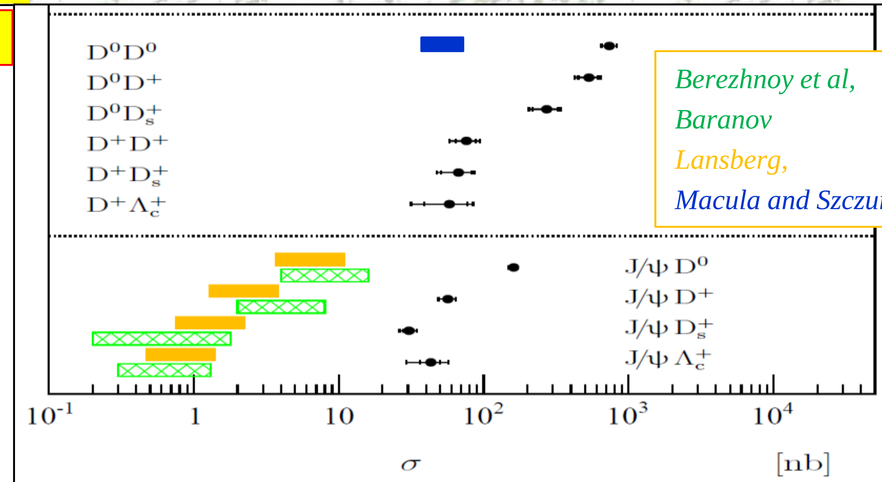


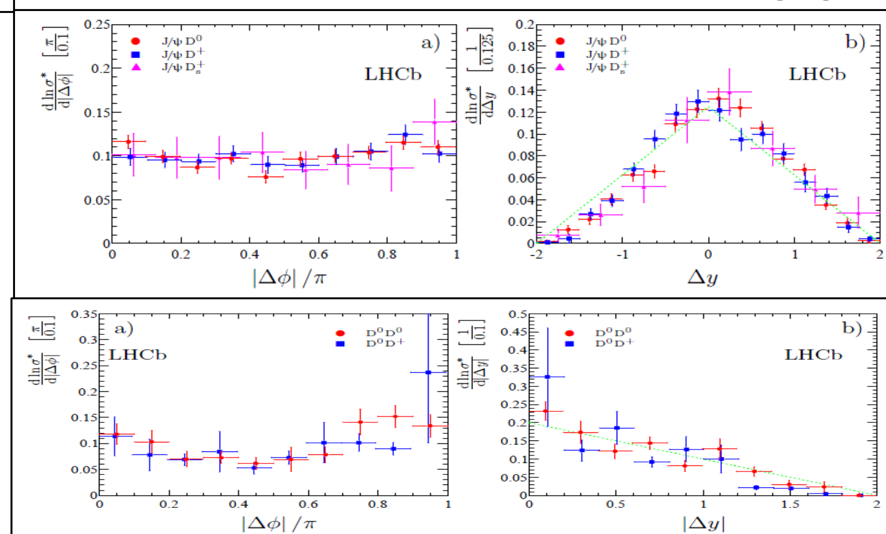
$J/\psi + c\bar{c}$ and $2\times c\bar{c}$ LHCb @7TeV

JHEP 1206(2012) 141, 1403(2014) 108

$\sqrt{s}$=7TeV, 355pb^{-1}

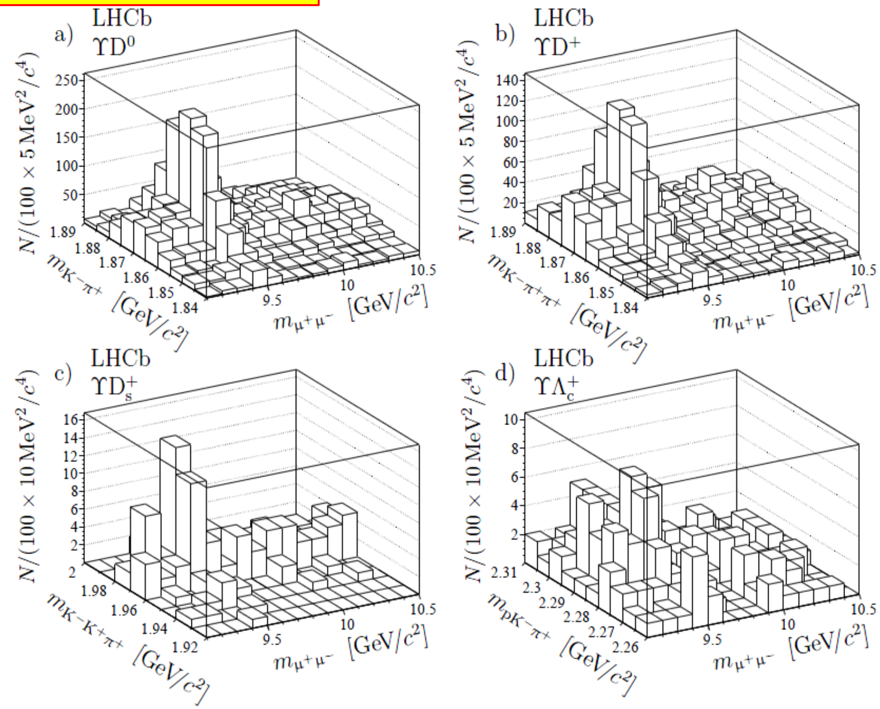






$\Upsilon + c\bar{c}$ LHCb @7&8TeV

JHEP 1607 (2016) 052



Signals	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
D^0	980 ± 50	184 ± 27	60 ± 22
D^+	556 ± 35	116 ± 20	55 ± 17
D_s^+	31 ± 7	9 ± 5	6 ± 4
Λ_c^+	11 ± 6	1 ± 4	1 ± 3

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\text{TeV}} = 155 \pm 21\,(\text{stat}) \pm 7\,(\text{syst})\,\text{pb},$$
$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\text{TeV}} = 82 \pm 19\,(\text{stat}) \pm 5\,(\text{syst})\,\text{pb},$$
$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\text{TeV}} = 250 \pm 28\,(\text{stat}) \pm 11\,(\text{syst})\,\text{pb},$$
$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\text{TeV}} = 80 \pm 16\,(\text{stat}) \pm 5\,(\text{syst})\,\text{pb},$$

$$\left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=7\,\text{TeV}} = (7.7 \pm 1.0)\,\%,$$
$$\left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\text{TeV}} = (8.0 \pm 0.9)\,\%,$$

Predictions:
SPS: (0.1-0.6)%
DPS O(10%)

$$\mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^0}_{\sqrt{s}=7\,\text{TeV}}}{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\text{TeV}}} = (13 \pm 5)\%,$$
$$\mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^0}_{\sqrt{s}=8\,\text{TeV}}}{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\text{TeV}}} = (20 \pm 4)\%,$$

$$\mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=7\,\text{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\text{TeV}}} = (22 \pm 7)\%,$$
$$\mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=8\,\text{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\text{TeV}}} = (22 \pm 6)\%,$$

Expected:
DPS: 25%

Υ+ $c\bar{c}$ LHCb @7&8TeV

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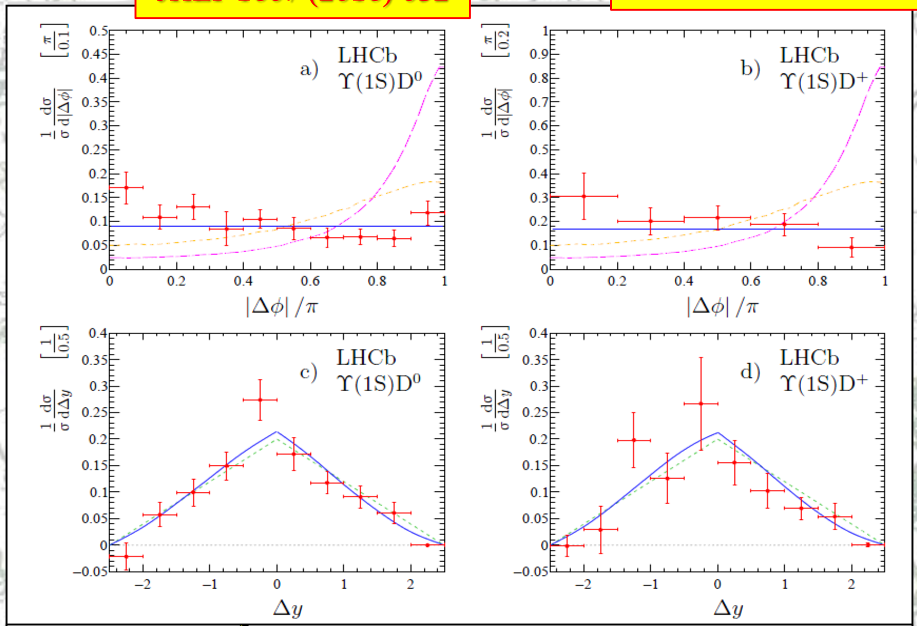
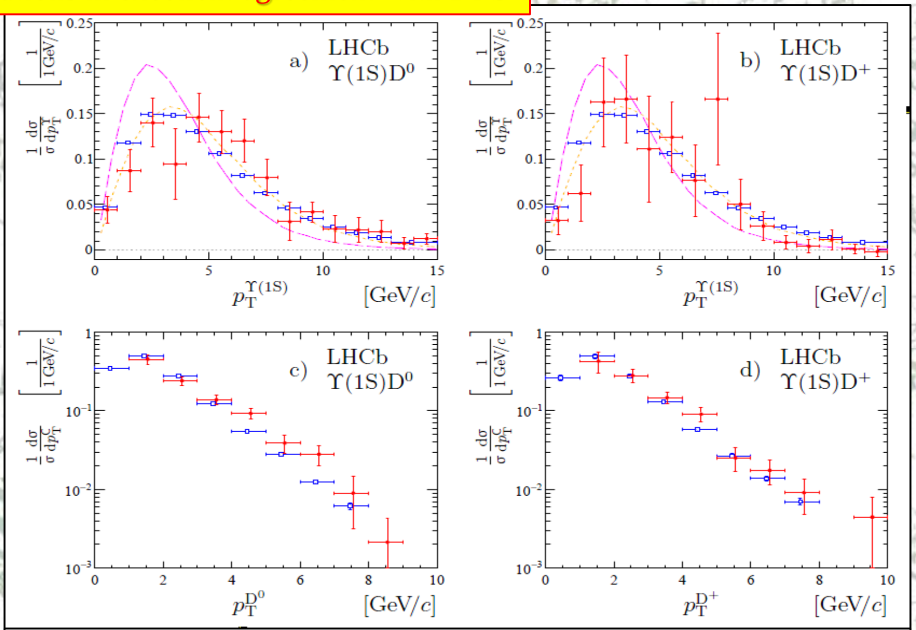
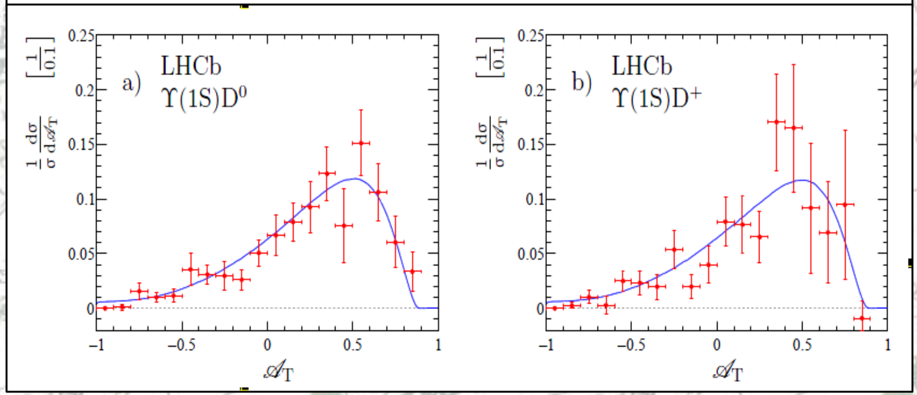
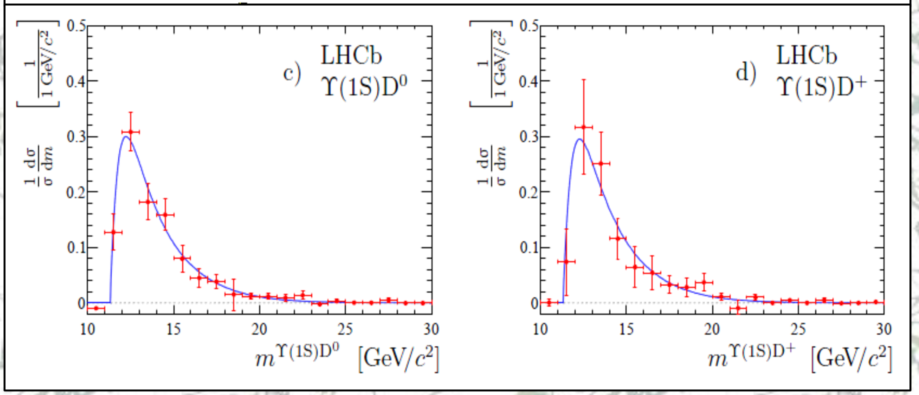
ALL differential distributions in excellent agreement with DPS









B_c pure SPS $c\bar{c} + b\bar{b}$

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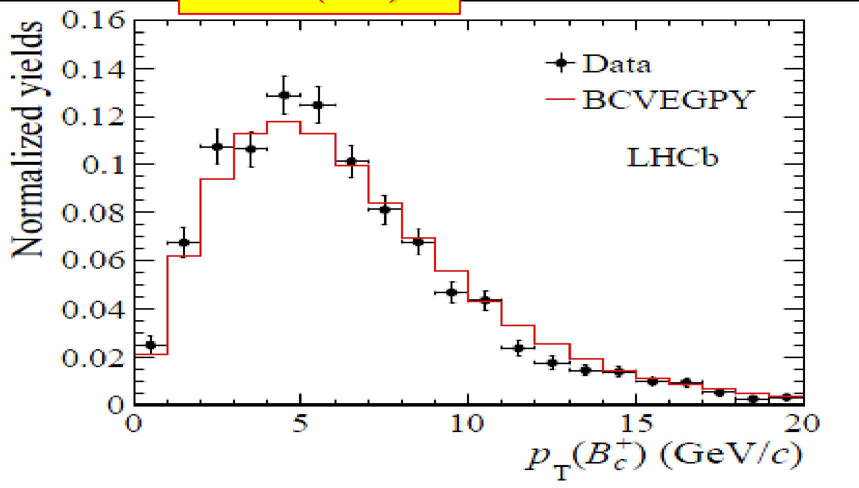
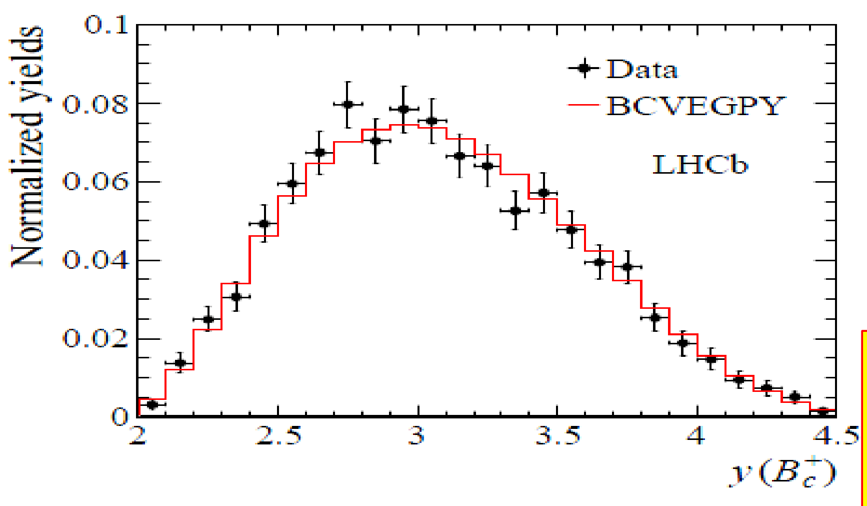


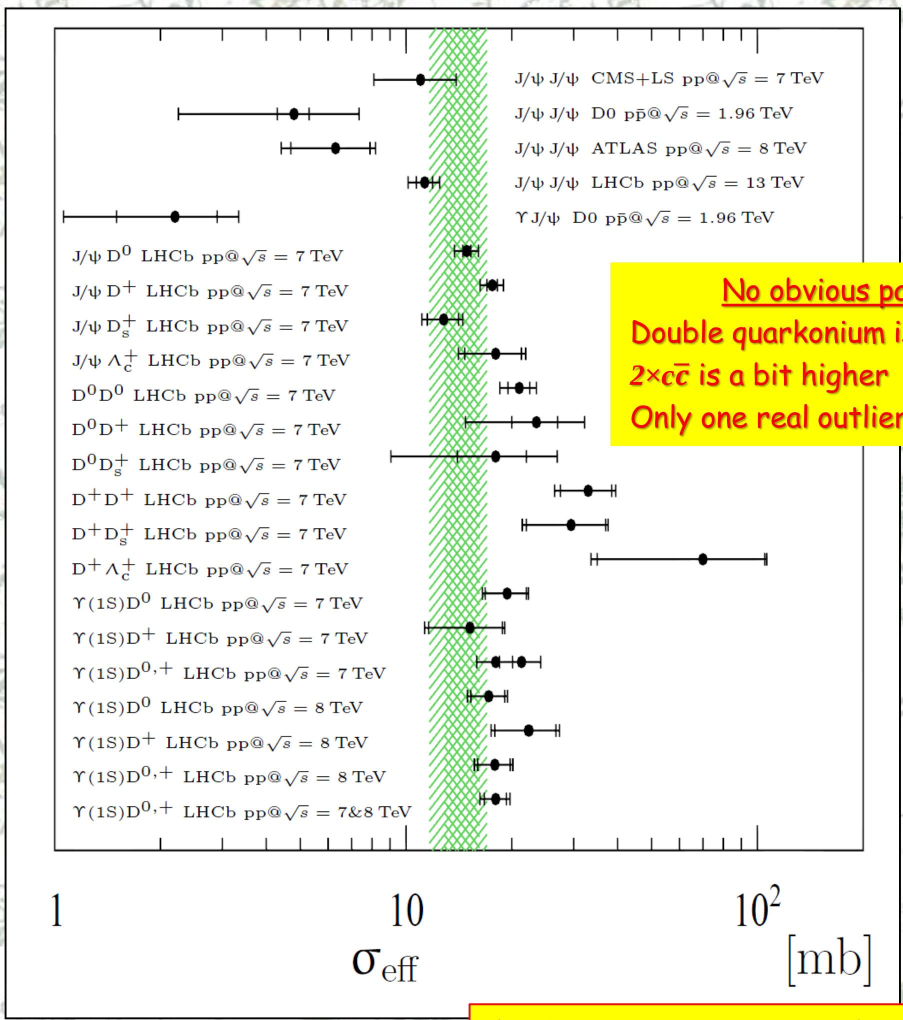


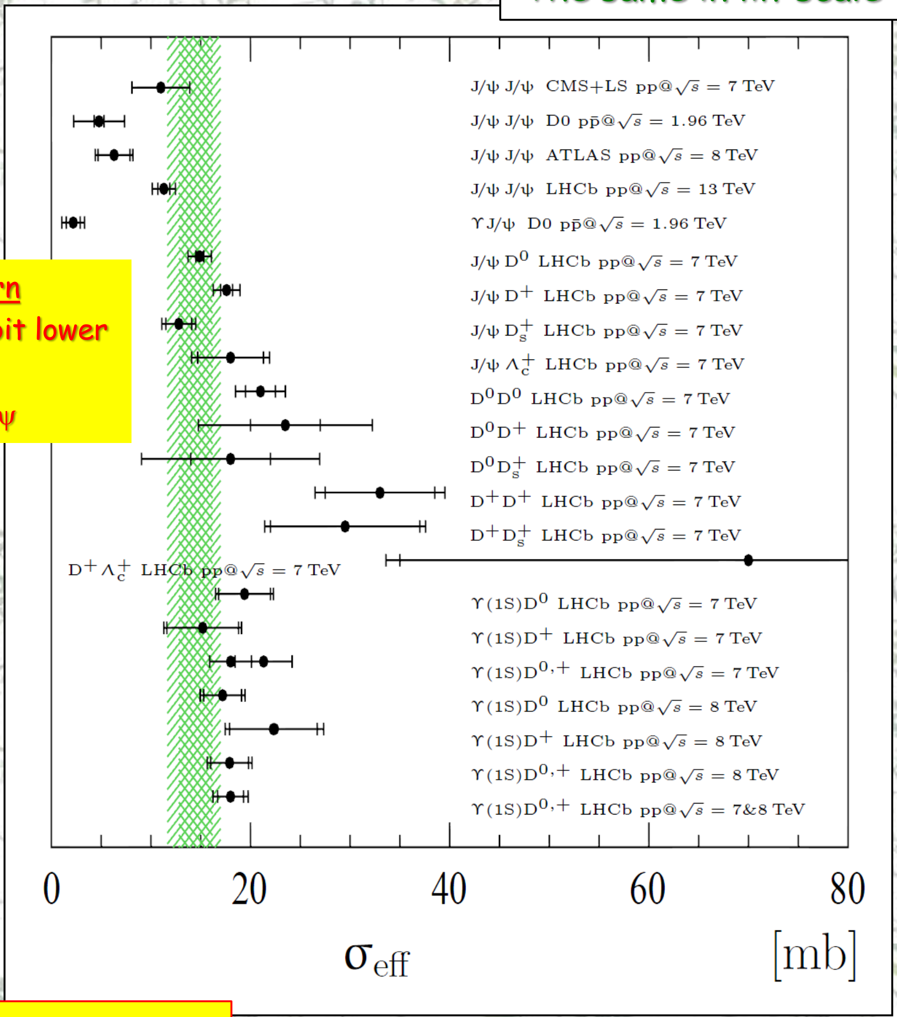
- Very special case:
  - ☺ Large signals, properties are well measured :
    - Mass , lifetime,
    - Ratios of Brs
  - ☺ differential rates in excellent $O(1\text{-}5\%)$ agreement with α_s^4 calculations
  - ☹ Overall rate is largely "unknown": no measured Br

Puzzle:
where are double heavy baryons Ξ_{cc} & Ξ_{bc}?
- also pure SPS
- essentially the same matrix element

σ_{eff}

The same in lin-scale





No obvious pattern

Double quarkonium is a bit lower

$2\times c\bar{c}$ is a bit higher

Only one real outlier $\Upsilon J/\psi$

"reference" σ_{eff} from multi-jet events by CDF

Summary

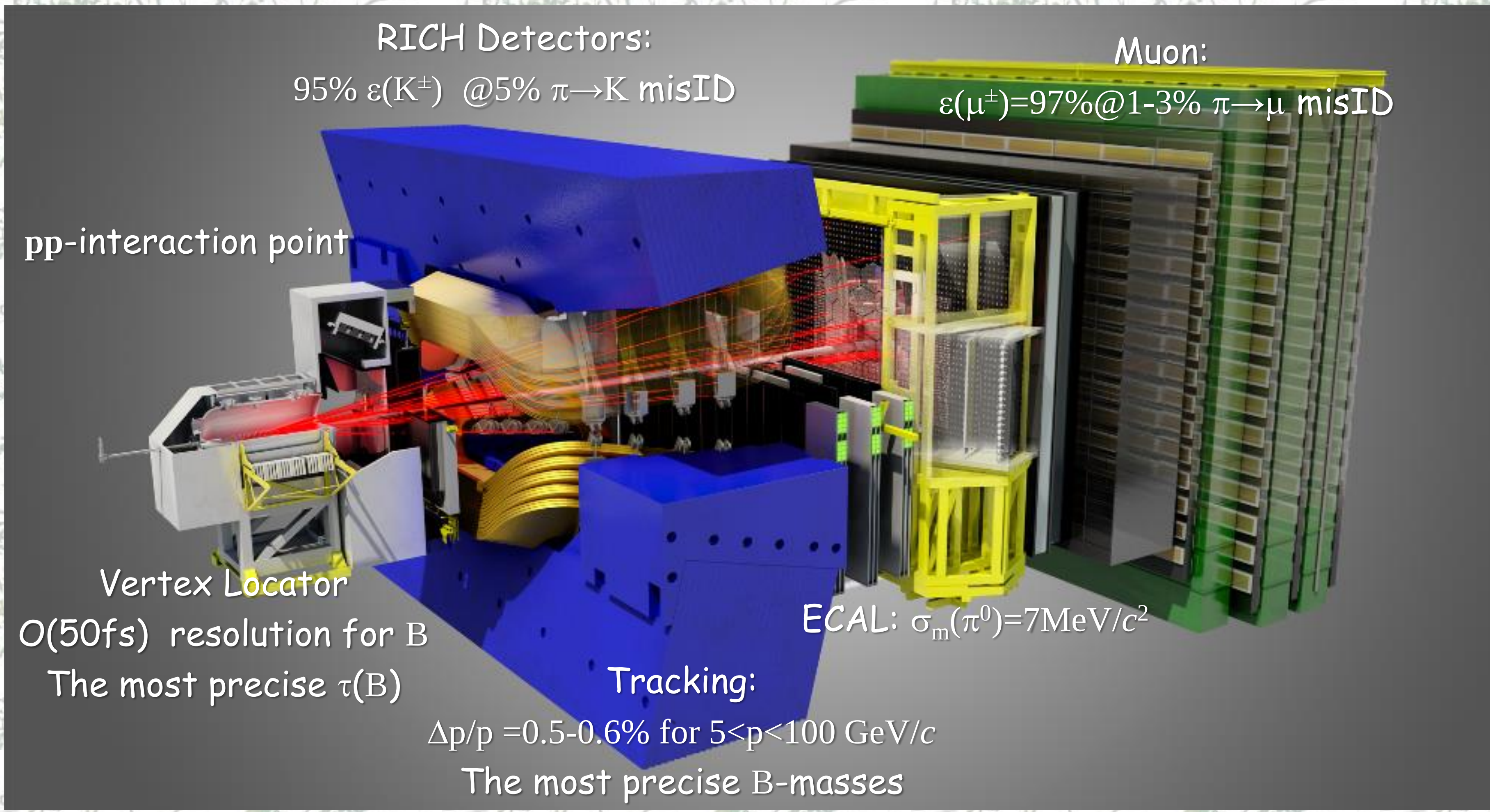
- Studies of multiquark production awaked after 30-35 years pause
- A lot of precise measurement suitable for QCD tests
- SPS: very important role of high order effect
  - Quarkonia: Color Octet contribution is small
- DPS with HQ is well established phenomenon
  - Allows DPS tests up to $p_T \sim 0$
  - DPS as expected is dominant at relatively low p_T
  - The most precise measurement of σ_{eff}
    - But even better precision is needed to probe universality of σ_{eff}
- None of LHC experiments analysed full Run-I/Run-II dataset yet: one can expect much better precision!

e.g. LHCb for $2\times J/\psi$: 4%, 0%, 18% of 7, 8 and 13TeV data

- Next step: multi HQ with open beauty?
- Next step: Triple Parton Scattering at Run-II? Macula, Szczurek, arXiv:1703.07163
  - Even larger multiplicity of charm and beauty!

Thank you!

~40% of heavy quarks in <4% of 4π



Too simple?

- Validity of factorization anzatz:

$$D_h^{ij}(x_1,x_2;Q_1^2,Q_2^2) = D_h^i(x_1;Q_1^2)D_h^j(x_2;Q_2^2).$$

- This anzatz allow $x_1+x_2>1$:
  - energy non-conservation. Need to suppress such configurations: at least $\theta(1-x_1-x_2)$ factor is needed
  - Makes integration impossible
- Numerical studies within Lund dipole cascade model shows violation of factorization at large Q_1^2 and/or Q_2^2
  - up to 20% deviation from factorization in γ+*jets* cross-sections in Tevatron case
  - Up to 30-50% for certain kinematical ranges
- For processes with (very) small x only factorization is fine

$$\Gamma_{gg}(b,x_1,x_2;\mu_1^2,\mu_2^2) = F_g(x_1,\mu_1^2)F_g(x_2,\mu_2^2)F(b;x_1,x_2,\mu_1^2,\mu_2^2),$$

$$\sigma_{\rm eff}(x_1,x_2,x_1',x_2',\mu_1^2,\mu_2^2) = \left(\int d^2bF(b;x_1,x_2,\mu_1^2,\mu_2^2)F(b;x_1',x_2',\mu_1^2,\mu_2^2)\right)^{-1}.$$